EXCITATION BY ROTATION OF FORCES

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Summary

Excitation by rotation of forces has been designed as addition to swept sine excitation and phase resonance method used during ground vibration tests of aircraft structures. The method is based on a multipoint excitation by in phase-shifted forces. With suitable distributed forces it is possible to excite also by a rotational moment of forces. The method is proposed mainly for excitation of centrally symmetrical structures. Arrangement of technical devices is described. The example from a modal test of a five-bladed propeller takes full advantage of this method.

1 INTRODUCTION

The aim of ground vibration tests of aircraft structures is to investigate their dynamical properties by means of modal parameters. Each mode of vibration is defined by natural frequency, modal damping value, mode shape and generalized mass. These parameters allow developing a mathematical model that is one of the main tools used for verification of the aircraft aeroelastic stability. Parameters of experimental model can also be used to update analytical FEM model.

Ground vibration tests of aircraft structures have an ultimate character. That means that all important modes in a frequency range of interest must be found and appropriate criteria must verify that modal parameters have been determined with acceptable uncertainty. The experimental method that fully meets these requirements is a phase resonance method. This method is based on separation of particular modes by means of appropriated excitation forces. Modal parameters are determined from a relation between known excitation forces and measured response of the structure that vibrate as one degree of a freedom system. Finding of an optimal set of excitation forces i.e. points of application, directions and magnitudes, is a basic condition for acceptable results. These conditions can be in most cases well fulfilled in the course of ground vibration tests of airplanes. But for some centrally symmetric structures like propellers or some spacecraft structures it can be even problematic to locate all modes of vibration that can be excited during an operational dynamic excitation. Such vibrations can be of course well simulated on multi-axial shaker tables developed during last years. The system of excitation given bellow does not mean to replace these expensive shaker tables but it suggests only how can the multipoint excitation system be utilized for vibration tests of centrally symmetric structures.

2 EXCITATION CIRCUITS

The signal generator of PRODERA is designed to deliver two waveforms 90° out of phase voltages with a stabilized amplitude and frequency. The forces control system includes two different units: one for the adjustment of the general level of forces, the other for individual adjustment of each force. This has been specially developed to set in amplitude and phase the force delivered by each exciter.

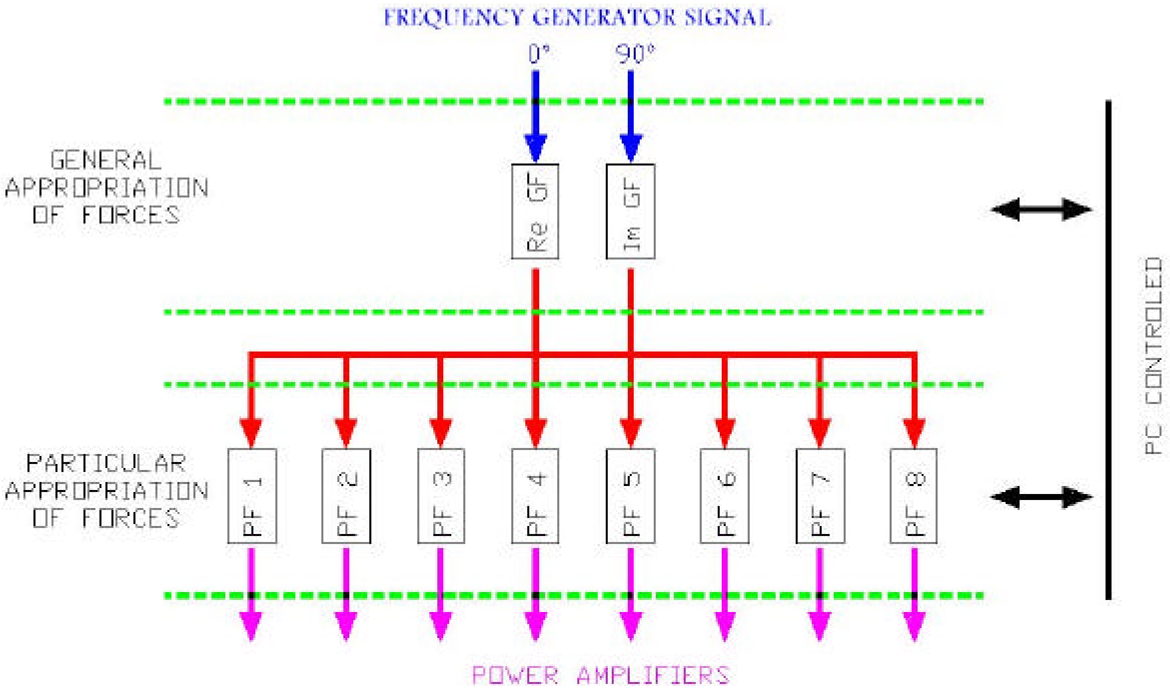

Figure 1: PRODERA force control system

There are two possibilities how to use an eight channel force control system, **globa**l and **individual mixing**:

- **Global mixing** of an in-phase signal with a 90° out of phase signal.

  Forces in particular channels are

$$F_1 = \mathrm{Re}\ F_1 + \mathrm{Im}\ F_1 = |F_1| \cos \omega t + i\,\lambda |F_1| \sin \omega t$$
$$F_2 = \mathrm{Re}\ F_2 + \mathrm{Im}\ F_2 = |F_2| \cos \omega t + i\,\lambda |F_2| \sin \omega t$$
$$\vdots$$
$$F_8 = \mathrm{Re}\ F_8 + \mathrm{Im}\ F_8 = |F_8| \cos \omega t + i\,\lambda |F_8| \sin \omega t$$

The ratio between an imaginary and real part is the same for all forces and is given by constant λ. This type of excitation is a basis for so called “forces in quadrature” method for determination of modal (generalized) mass and damping.

At phase resonance method there are individual modes of vibration of the tested structure excited to behave as one degree of freedom.

The corresponding generalized excitation force is at natural frequency real and has the following form

$$\Phi_r = \mathrm{Re}\,\Phi_r = \sum_{j=1}^{n} F_j S_{rj}$$

where S_{rj} is normalized displacement measured in the point and direction of the force F_j, index r is designation of an investigated mode.

After introduction imaginary components of excitation forces the generalized force is complex

$$\Phi_r = \mathrm{Re}\,\Phi_r + \mathrm{Im}\,\Phi_r = \sum_{j=1}^{n} F_j S_{jr} + i\,\lambda \sum_{j=1}^{n} F_j S_{jr}$$

Imaginary components introduced in this way cause that natural frequency ω_r will increase or decrease according to a sign of imaginary generalized force. From the change of natural frequency generalized mass and damping can be calculated.

- **Individual mixing** of an in-phase signal with a 90° out of phase signal.

The association of two particular appropriation units (one output being 90° shifted) allows adjusting the phase of each excitation channels. In this case 8 particular appropriation units will drive only 4 excitation channels. Forces in particular channels are

$$\begin{aligned}
F_1 &= \mathrm{Re}\,F_1 + \mathrm{Im}\,F_1 = \rho_1 |F_1| \cos\omega t + i\,\lambda_1 |F_1| \sin\omega t \\
F_2 &= \mathrm{Re}\,F_2 + \mathrm{Im}\,F_2 = \rho_2 |F_2| \cos\omega t + i\,\lambda_2 |F_2| \sin\omega t \\
F_3 &= \mathrm{Re}\,F_3 + \mathrm{Im}\,F_3 = \rho_3 |F_3| \cos\omega t + i\,\lambda_3 |F_3| \sin\omega t \\
F_4 &= \mathrm{Re}\,F_4 + \mathrm{Im}\,F_4 = \rho_4 |F_4| \cos\omega t + i\,\lambda_4 |F_4| \sin\omega t
\end{aligned}$$

For the following demonstration of **principle of excitation by rotation of forces** a special distribution of forces is used when $\lambda_1 = \rho_2 = \rho_3 = \rho_4 = \lambda_3 = \lambda_4 = 0$ and $\rho_1 |F_1| = \lambda_2 |F_2| = |F|$

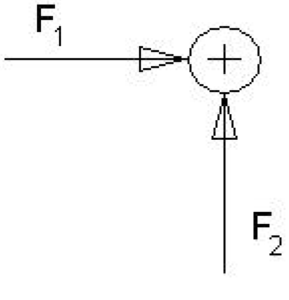

Figure 2: Excitation forces are mutually oriented in perpendicular direction

Particular forces are

$$F_1 = r_1 |F_1| \cos wt = |F| \cos wt$$
$$F_2 = l_2 |F_2| \sin wt = |F| \sin wt$$

and the resultant modulus of excitation force F given by addition of both force vectors is

$$F = |F| \cos wt + i|F| \sin wt$$

The resultant force pass the intersection of the forces F_1 and F_2 and turns around this point for 2Π during one time period $t = T = 1/f$

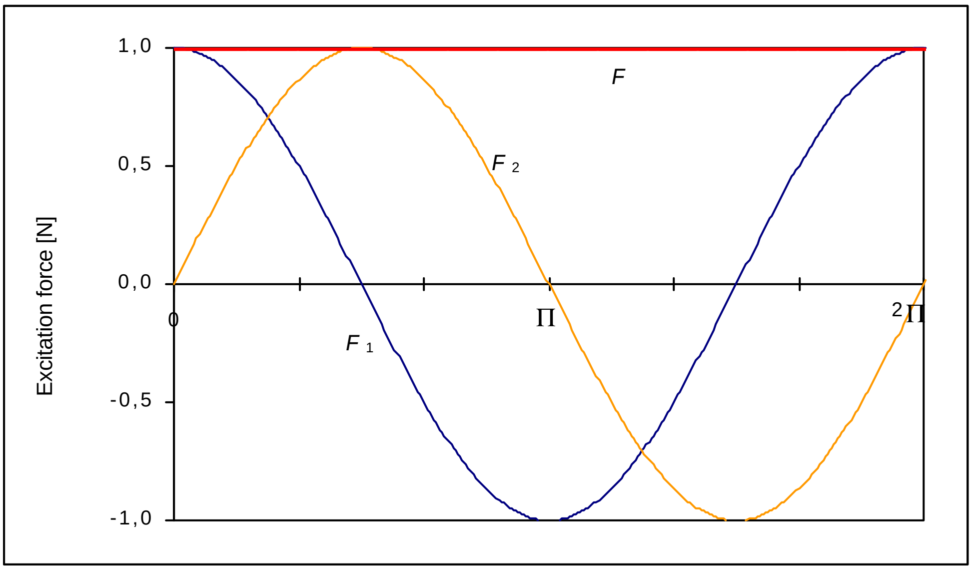

Figure 3: Waveform of excitation forces

3 EXCITATION OF AN AIRCRAFT PROPELLER

3.1 Procedure of a test process

The experimental investigation of structural vibration is performed in order to describe dynamics of a structure in frequency range of interest. To be able to fulfil this task it is necessary to solve two problems – to find all modes and to excite them in such a way that the modal parameters will be reliably determined. Both these problems have a common solution – the appropriate set of excitation forces that will intensify sufficient energy to particular modes.

A multiple points excitation system is successfully used for ground vibration tests of aircraft structures and is well described. Less information are known for example about excitation of airspace structures or also aircraft propellers.

The following example is from the modal test of five bladed aircraft propeller carried out in the VZLU Modal test laboratory within a framework of an engine - propeller coupled vibration research.

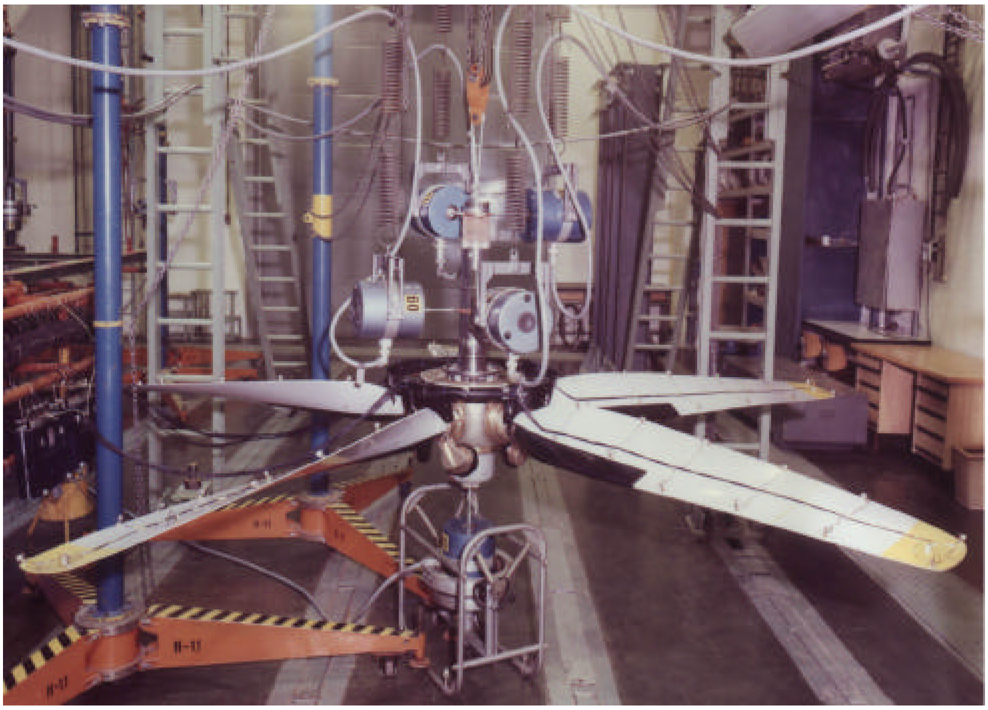

Figure 4: Special arrangement of a multiple exciter system used for a modal test of a five bladed propeller

The propeller with shaft is suspended in vertical position on the spring so that the resonance frequency of the propeller on the suspension is very low less than 1 Hz. The point of suspension is in the centre of gravity (CG) of the propeller with shaft. The propeller was excited at four points on the propellers shaft and at one point at propellers head.

The excitation system was formed by electrodynamics exciters. On propeller's blades there were 65 miniature accelerometers whose mass is only 1g. Another five accelerometers were on the propellers shaft. On each blade there were six couples of accelerometers oriented in the direction perpendicular to the propeller's surface (measurement in the direction of minimal stiffness). On the tip of each blade there was one accelerometer oriented in the direction of propellers chord line (direction of maximal stiffness). Schematic illustration of an exciters arrangement is on the Figure 5.

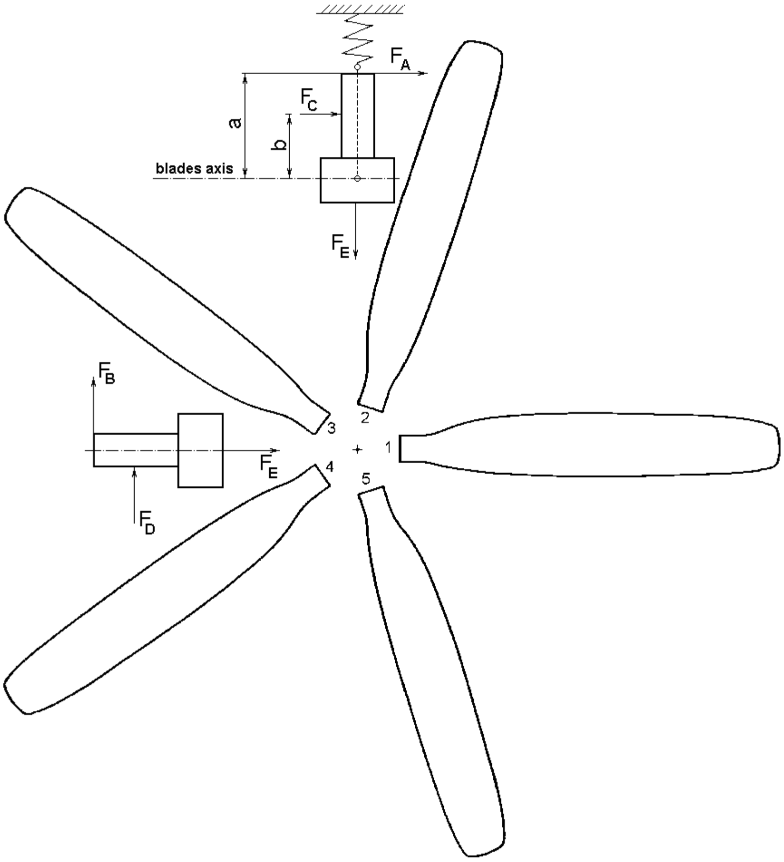

Figure 5: Arrangement of five exciters for modal test of a propeller

Exciters on the propellers shaft act in the direction perpendicular to the shaft axis. Two exciters introducing forces F_A and F_B are on the free end of the shaft. The force F_A acts in the direction of the blade 1 and the force F_B is perpendicular to it. The distance of F_A and F_B from the propeller with a shaft system CG is a. Another two exciters introducing forces F_C and F_D are close to propeller's head in distance b from the CG. The force F_C is in the direction of the blade 1 and the force F_D is perpendicular to it. Force F_E on the propeller's head has a direction coincident with the propeller's shaft axis.

By combination of forces F_A, F_B, F_C and F_D four different types of excitation can be created. Two synchronous types with all forces in phase or in phase opposition and two types based on a rotation of forces.

- Synchronous force excitation

$$a\,F_A = -b\,F_C$$
$$a\,F_B = -b\,F_D$$

The resulting force acts in the plane of the propeller and is perpendicular to its axis of a rotation. The direction of the force is given by arctg F_B/F_A

The resulting moment of forces is zero.

- Synchronous momental excitation

$F_A = - F_C$
$F_B = - F_D$

The propeller is exited only by a moment of forces with direction arctg F_B/F_A

- Excitation by rotation of forces

$a\ \mathrm{Re}F_A = - b\ \mathrm{Re}F_C$
$a\ \mathrm{Im}F_B = - b\ \mathrm{Im}F_D$

when $F_A = F_B$

The resulting force acts in the plane of the propeller and is perpendicular to its axis of a rotation while the moment is zero

- Excitation by rotation of a moment of forces

$\mathrm{Re}F_A = - \mathrm{Re}F_C$
$\mathrm{Im}F_B = - \mathrm{Im}F_D$

when $F_A = F_B$

The propeller is excited only by a rotational moment

3.2 Evaluation of test results

Utilization of the introduced excitation system including rotation of forces and moments is demonstrated on mode shapes and frequency responses of three different types of a propellers' vibration:

- centrally symmetrical modes
- non- symmetrical reactive modes
- non-symmetrical non-reactive modes

3.2.1 Centrally symmetrical modes

On the pictures there are shapes of two centrally symmetrical modes S_1 and S_2. The force F_E in the direction of propeller's shaft well excites all centrally symmetrical modes. Complex components in the right corners of the pictures with mode shapes indicate that all measured points on the propeller reach the maximum in the same instant which means that the phase criteria is well fulfilled and that all modal parameters can be determined with a high accuracy. Centrally symmetrical modes can be also well indicated by rotation of a moment of forces.

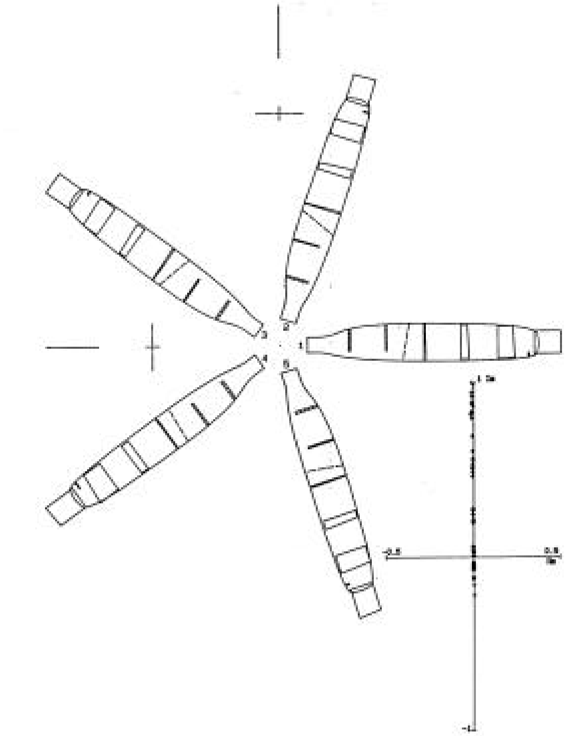

Figure 6: Symmetrical mode S_1 – 23.96 Hz

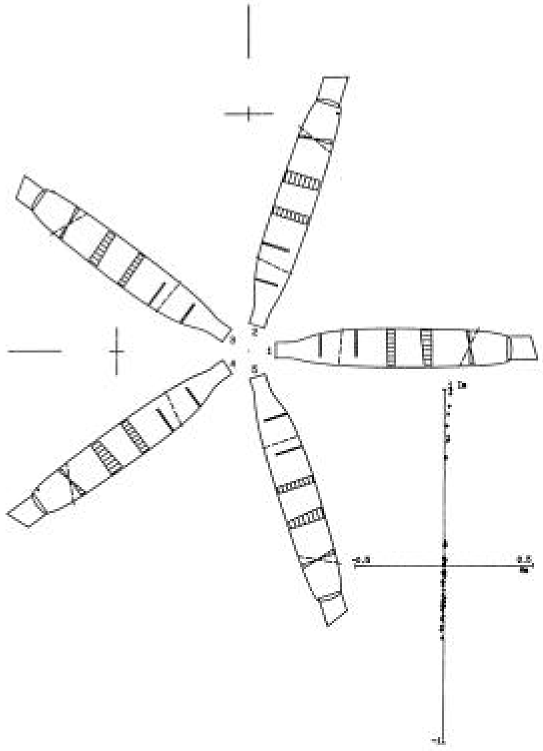

Figure 7: Symmetrical mode S_2 – 76.37 Hz

3.2.2 Non-symmetrical reactive modes

On the pictures there is presented a typical non-symmetrical reactive mode with two different mode shapes and with two very close resonance frequencies. This type of propellers modes can be excited by synchronous as well as by rotational system of forces. Advantages and disadvantages of particular excitation types will be demonstrated on graphs with frequency responses measured during a modal test of the propeller.

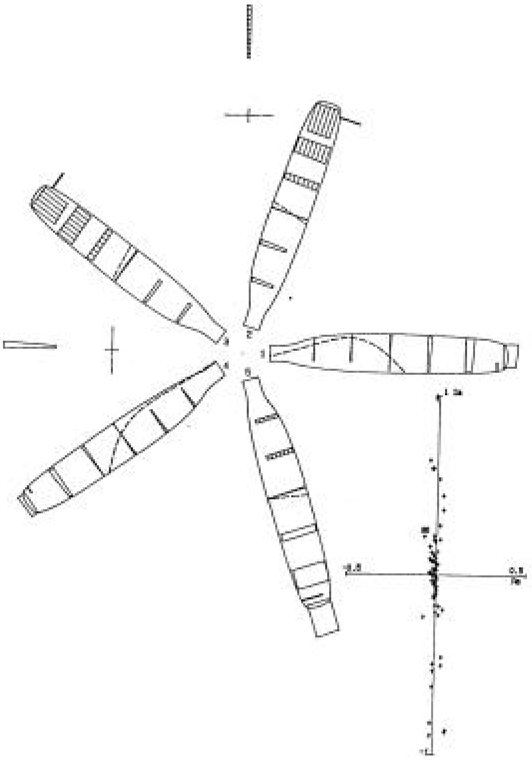

Figure 8: Non-symmetrical reactive propeller mode $R_{1\text{-}1}$ – 26.64 Hz

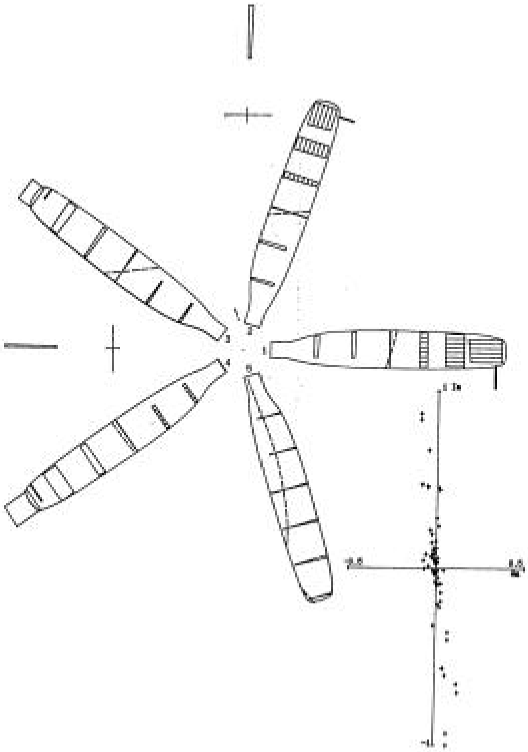

Figure 9: Non-symmetrical reactive propeller mode $R_{1\text{-}2}$ – 26.79 Hz

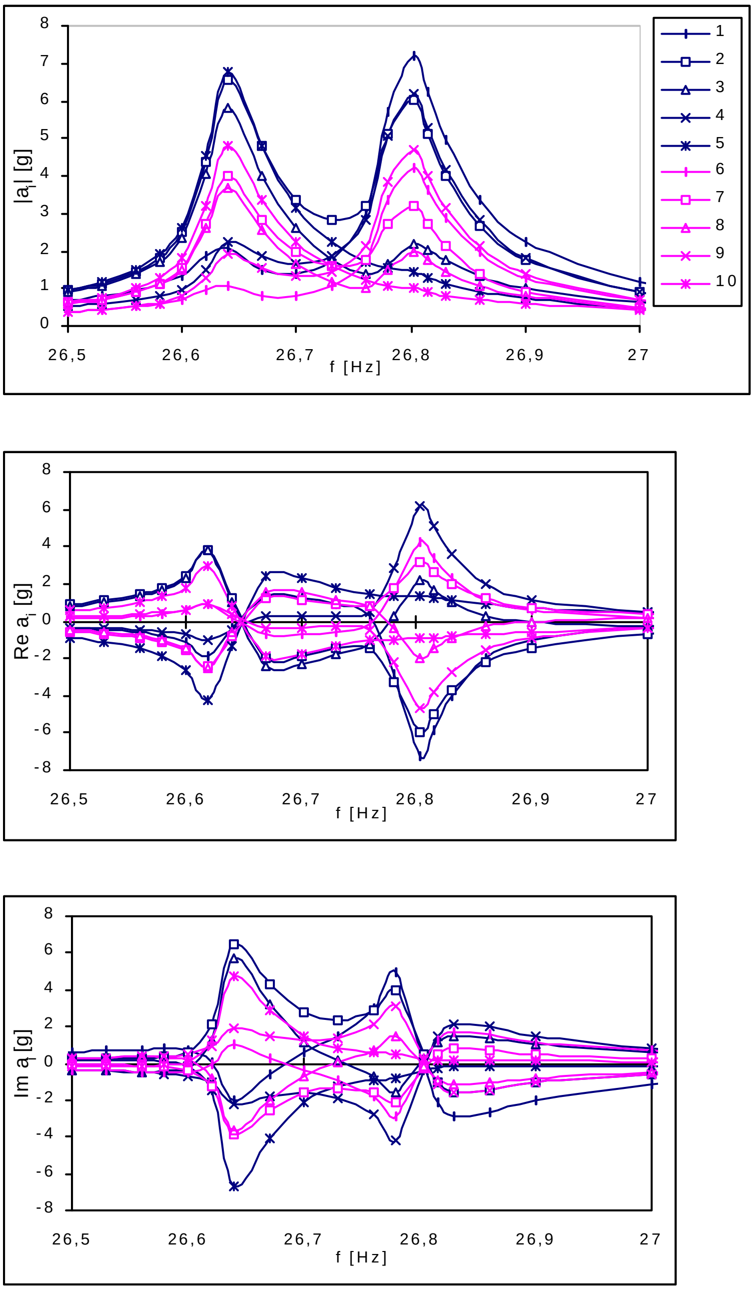

Figure 10: Frequency response of the propeller in a frequency range of the mode R_1 (R_{1-1}, R_{1-2}). Excitation was by rotation of a moment of forces.

Accelerations were measured on the propeller's blades tips in the direction perpendicular to blades surfaces (blue colour) and in the plane of blades surfaces in a direction of chord lines (red colour). From the graphs it is apparent that the first resonance frequency corresponds with the minimum of real components and the second resonance frequency with the minimum of imaginary components.

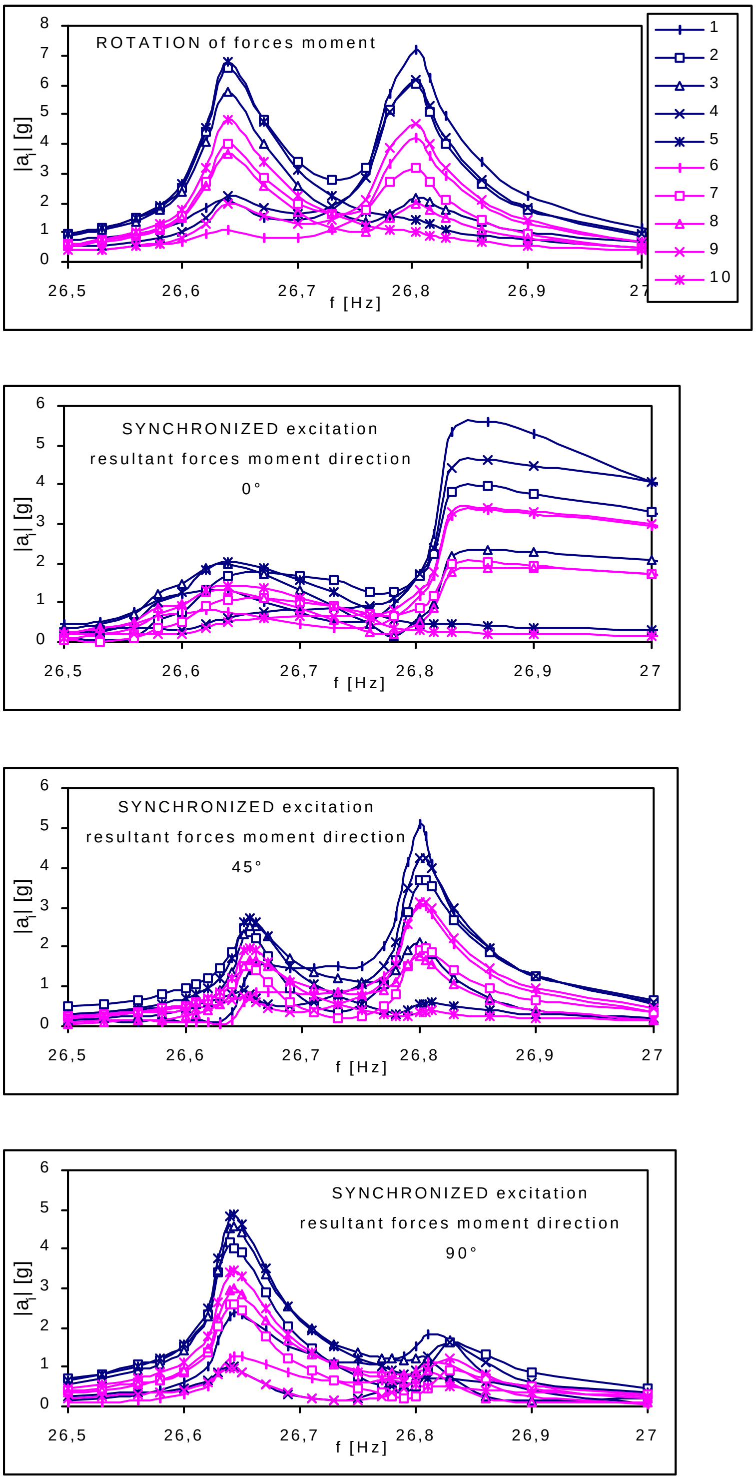

Figure 11: Frequency response of the propeller in a frequency range of the mode R_1 (R_{1-1}, R_{1-2}). Excitation was by rotation of a moment of forces and by moment of synchronous forces

These graphs show advantage of rotational excitation in this case excitation by rotation of a moment of forces. From the first picture it is well seen how both shapes R_{1-1} and R_{1-2} are by rotational excitation well excited. Next three graphs demonstrate how the response is dependent on the direction of the resultant forces moment in the case when synchronized excitation is used. The direction is for each of two shapes different. 0° is bad for both shapes, 45° is better for the second shape and 90° for the first one.

On the Figures 12 and 13 there is another non-symmetrical reactive mode of the propeller again with two mode shapes and two very close resonance frequencies

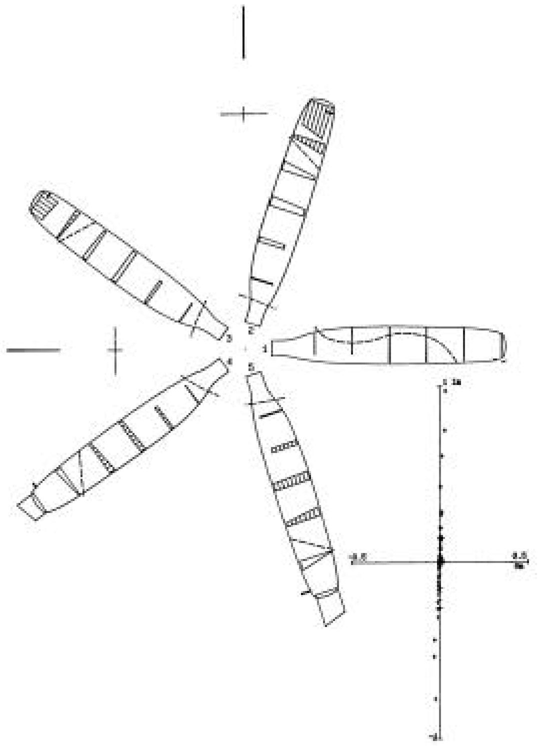

Figure 12: Non-symmetrical reactive propeller mode R_{2-1} – 55.50 Hz

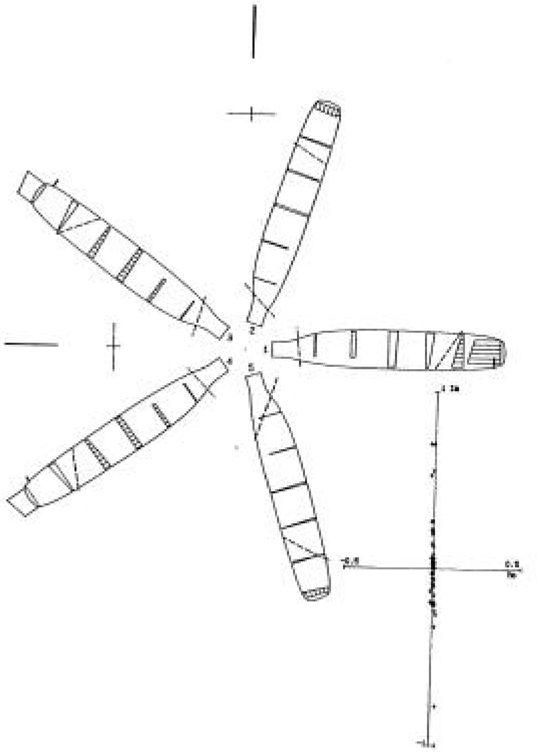

Figure 13: Non-symmetrical reactive propeller mode R_{2-2} – 55.55 Hz

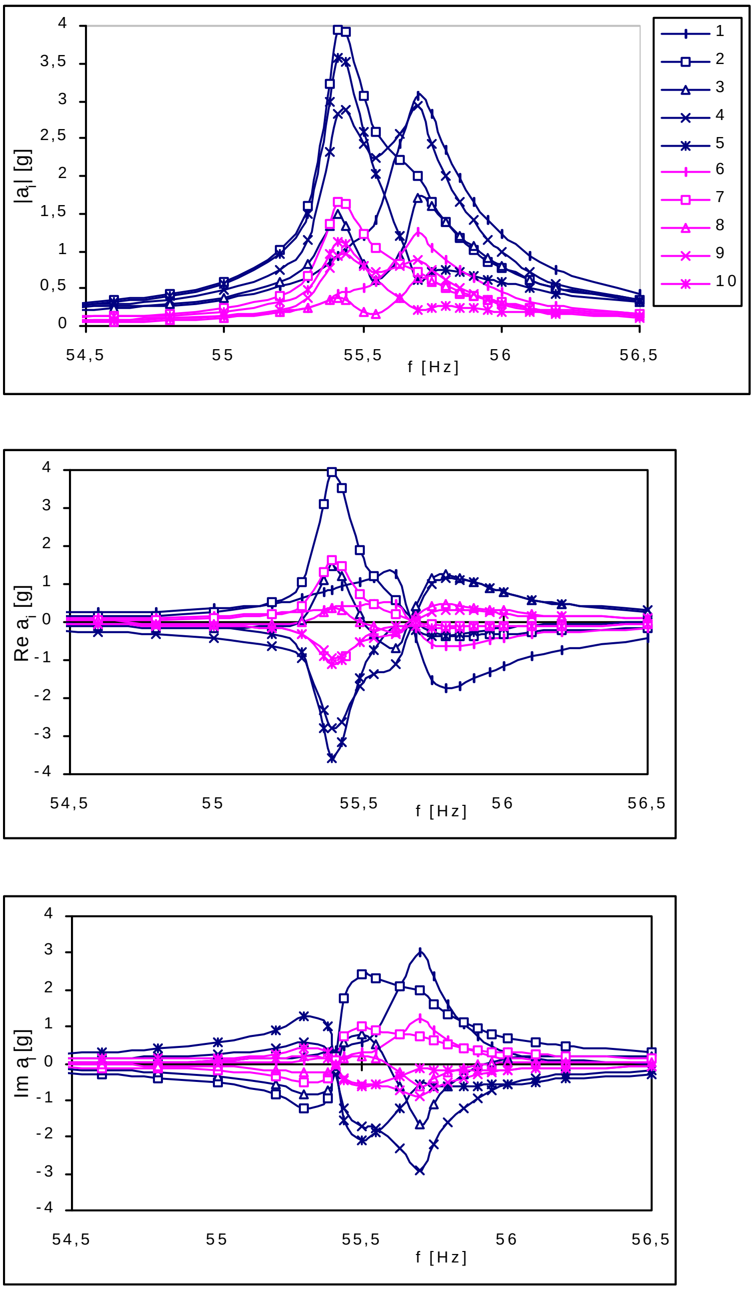

Figure 14: Frequency response of the propeller in a frequency range of the mode R_2 (R_{2-1}, R_{2-2}). Excitation was by rotation of forces.

Accelerations were measured on the propeller's blades tips in the direction perpendicular to blades surfaces (blue colour) and in the plane of blades surfaces in a direction of chord lines (red colour). From the graphs is apparent that the first resonance frequency corresponds with the minimum of imaginary components and the second resonance frequency with the minimum of real components, which is reverse in comparison with excitation by rotation of a moment.

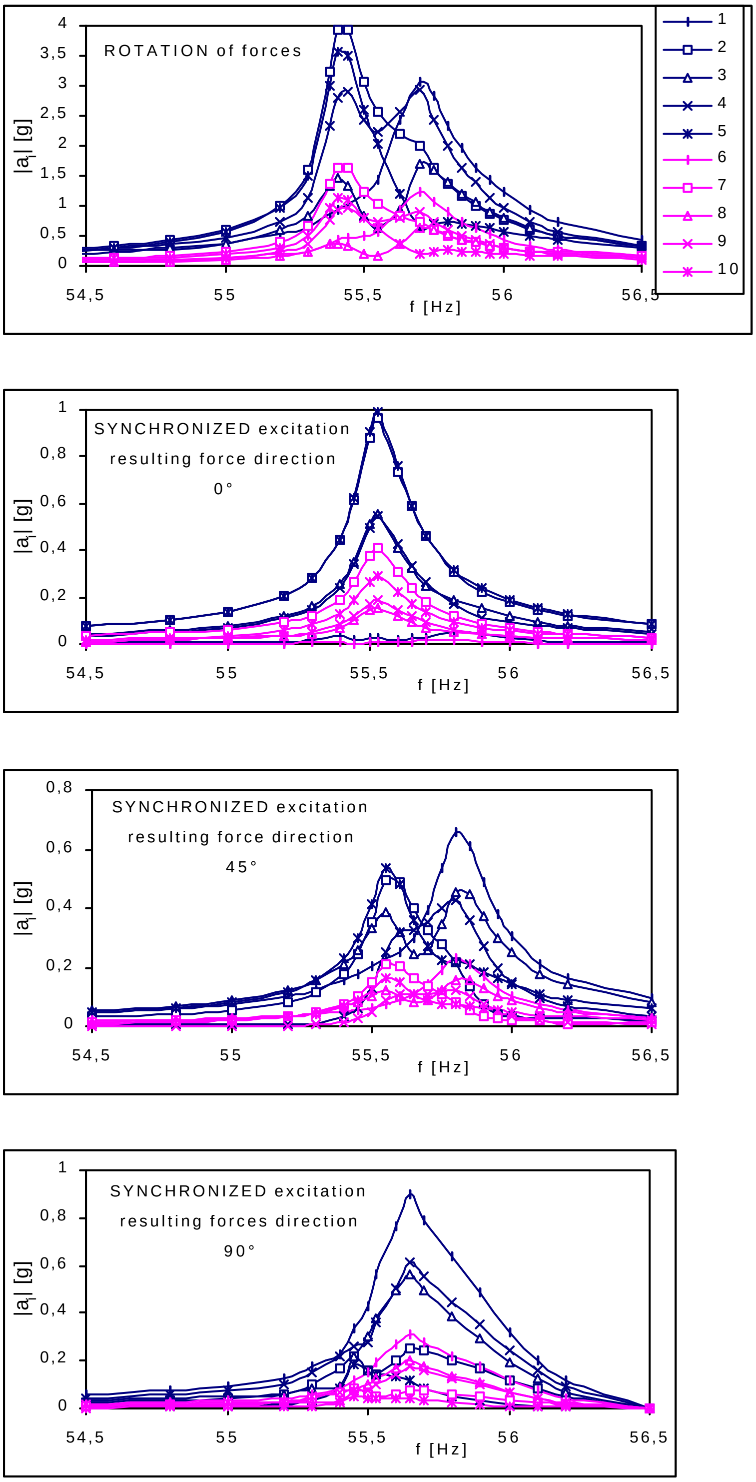

Figure 15: Frequency response of the propeller in a frequency range of the mode R_2 (R_{2-1}, R_{2-2}). Excitation was by rotation of forces and by synchronous forces

These graphs show again advantage of rotational excitation in this case by rotation of forces. Both modes R_{2-1} and R_{2-2} are well excited by rotational excitation, which is obvious from the graph. The next three graphs demonstrate as in the previous example how the response is dependent on the direction of synchronized forces.

3.2.3 Non-symmetrical non-reactive modes

On the Figures 16 and 17 there is a typical non-symmetrical non-reactive mode of a propeller. Two resonance frequencies are very close. Contrary to reactive modes excitation of non-reactive modes is much more difficult. One of possible solutions is an excitation by rotation of a moment of forces. Another possibility is an excitation by a moment of synchronous forces oriented in the proper direction.

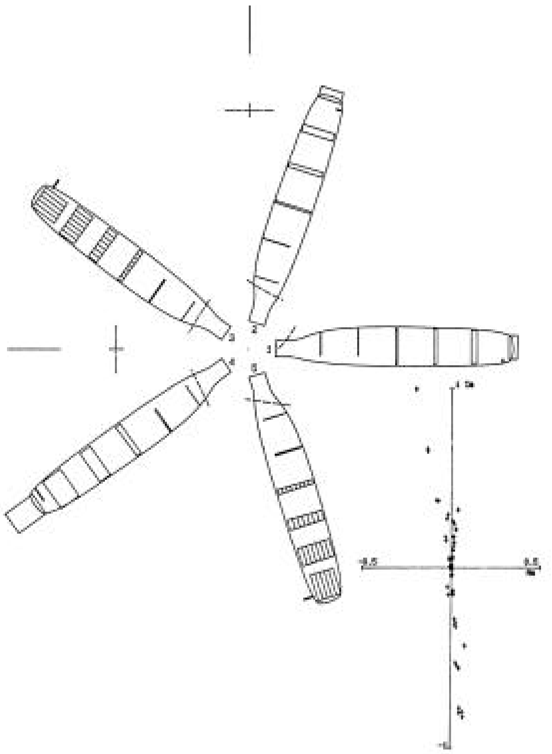

Figure 16: Non-symmetrical non-reactive propeller mode N_{1-1} - 20.45 Hz

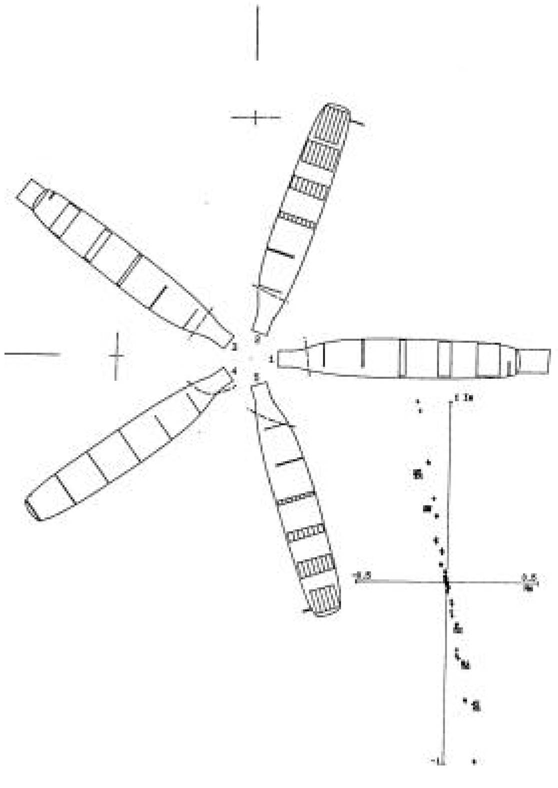

Figure 17: Non-symmetrical non-reactive propeller mode N_{1-2} - 20.74 Hz

4 CONCLUSION

The excitation by rotation of forces has been successfully applied at various modal tests of aircraft propellers. The main contribution as obvious from the previous demonstrations consists in the reliable identification of all types of propeller vibrations including in frequency close modes. Rotation of forces is increasing methodical possibilities of the multipoint excitation system, it is very close to operational excitation of propellers and engines and can also help excite spacecraft structures whose significant characteristics of dynamic loads are their multiaxial operations.